

# Effect of mechanical stresses on coercive force and saturation remanence of ensemble of dual-phase interacting nanoparticles

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**Abstract.** In the dual-phase model of interacting nanoparticles stretching leads to a decrease in both coercive force  $H_c$  and saturation remanence  $I_{rs}$ , and compression to their growth. Magnetostatic interaction between particles also decreases both  $H_c$  and  $I_{rs}$ . Theoretical analysis was carried out in the framework of the dual-phase system of interacting particles on the example of nanoparticles  $\gamma\text{-Fe}_2\text{O}_3$ , epitaxially coated with cobalt.

## Introduction

An important factor affecting the process of magnetization of an ensemble of small (single-domain) particles is their magnetostatic interaction. For example, consider a system of  $N$  magnetic grains of size  $a$ , uniformly distributed in a nonmagnetic matrix. The field produced by each of these particles on the neighboring can be estimated as  $H_m \sim 2I_s N a^3 / R^3 = 2cI_s$ , where  $R$  the average distance between particles,  $c = N a^3 / R^3$  volume concentration of magnetic material in the system. In the materials for magnetic recording, magnetics with high values of spontaneous magnetization ( $I_s \sim 350 - 500$  G) is commonly used. Therefore, at concentrations  $c \sim 0.1 - 0.2$ , magnetostatic interaction may have significant influence on magnetization of the low-coercive particles.

To analyze the effect of magnetic interaction on the magnetization of an ensemble of chemically inhomogeneous nanoparticles, we use the model of dual-phase particles, described in detail in [1]:

## Model

1. Homogeneously magnetized nanoparticle (phase 1) of volume  $V$  has the form of ellipsoid with elongation<sup>1</sup>  $q_1$ , and its long axis is oriented along the  $Oz$ -axis (see Fig. 1).
2. Nanoparticle contains an uniformly magnetized ellipsoidal inclusion (phase 2) with a volume  $v = \varepsilon V$  and elongation  $q$ .
3. It is considered that the axes of crystallographic anisotropy of both uniaxial ferromagnets are parallel to the long axes of the ellipsoids, and the vectors of spontaneous magnetization of phases  $\mathbf{I}_s^{(1)}$  and  $\mathbf{I}_s^{(2)}$  lie in the plane  $yOz$ , that contains the long axes of the magnetic phases, and make angles  $\theta^{(1)}$  and  $\theta^{(2)}$  with the  $Oz$  axis, respectively.
4. Both external magnetic field  $H$  and uniaxial mechanical stresses  $\sigma$  are applied along the  $Oz$ -axis.

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<sup>1</sup>Elongation the ratio of the length  $a$  of semi-major axis of the ellipsoid to the length  $b$  of semi-minor one.

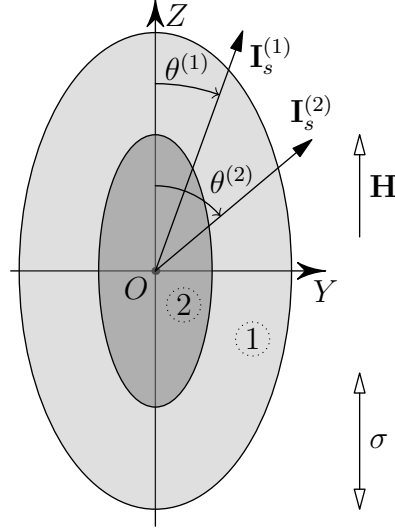


Figure 1: Illustration to the model of dual-phase particle

5. The volume of nanoparticles exceeds the volume of superparamagnetic transition. In other words, thermal fluctuations are not taken into account.

The calculation of fields of magnetostatic interaction between dual-phase particles was performed using the method of the random field interaction [2, 3]. It was found that at low concentrations of magnetic nanoparticles in a nonmagnetic matrix ( $c < 0.1$ ) the distribution function of the projection of the field interaction on the direction of the external magnetic field  $\mathbf{H}$  is described by the Cauchy law:

$$W(h) = \frac{1}{\pi} \frac{B}{B^2 + (h - \alpha I)^2}, \quad (1)$$

where  $\alpha = 8\pi/(5 - \hat{N})$ ,  $\hat{N}$  the demagnetization factor. Parameter  $B$  and magnetization  $I$  are determined by the system of equations:

$$\begin{cases} B = 5c \int \{(N_1 + N_3) [I_{s1}(1 - \varepsilon) + I_{s2}\varepsilon] + (N_2 + N_4) |I_{s1}(1 - \varepsilon) - I_{s2}\varepsilon|\} W(h) dh, \\ I = c \int \{(N_1 - N_3) [I_{s1}(1 - \varepsilon) + I_{s2}\varepsilon] + (N_2 - N_4) [I_{s1}(1 - \varepsilon) - I_{s2}\varepsilon]\} W(h) dh, \end{cases} \quad (2)$$

where  $\varepsilon = v/V$  relative volume of the second phase (inclusion),  $V$  volume of nanoparticle,  $v$  volume of inclusion. According to [1, 4],  $N_1$  is the number of particles, whose magnetic moments of both phases are parallel to the external field  $\mathbf{H}$ ;  $N_2$  is the number of particles with the magnetic moments of the first phase that are parallel to  $\mathbf{H}$  and the magnetic moments of the second phase are antiparallel to  $\mathbf{H}$ . (If we consider  $\mathbf{H}$  to be directed upward, then we can denote the first state as  $\uparrow\uparrow$ , the second one as  $\uparrow\downarrow$ , the third one as  $\downarrow\downarrow$ . and the last one (4th) as  $\downarrow\uparrow$ . The corresponding numbers of particles in each of these states we denote as  $N_1$ ,  $N_2$ ,  $N_3$  and  $N_4$ .)

In the case of large concentrations ( $c > 0.1$ ), the distribution of the random field interaction obeys the normal law:

$$W(h) = \frac{1}{\sqrt{2\pi}B} \exp \left\{ -\frac{(h - \tilde{\alpha}I)^2}{2B^2} \right\}, \quad (3)$$

where

$$B = c \sqrt{\int \{ (N_1 + N_3) [I_{s1}(1 - \varepsilon) + I_{s2}\varepsilon] + (N_2 + N_4) |I_{s1}(1 - \varepsilon) - I_{s2}\varepsilon| \}^2 W(h) dh}, \quad (4)$$

and the magnetization  $I$  is given by the same equation as in (2).

The obtained self-consistent equations (1)–(4) allow us to estimate the characteristic field interaction  $B$ , and to calculate the magnetization  $I$  of the system of dual-phase interacting nanoparticles.

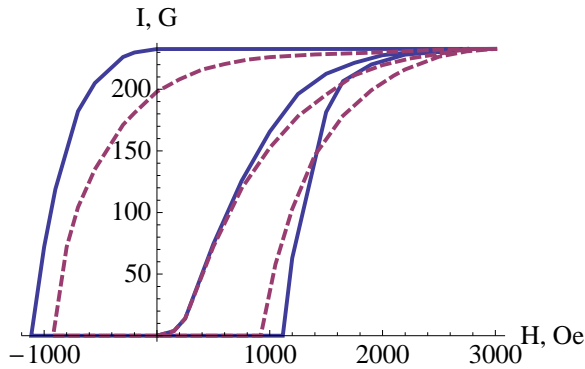


Figure 2: Hysteresis loops and magnetization curves of ensemble of non-interacting (*solid curve*,  $c = 0$ ) and interacting (*dashed curve*,  $c = 0.24$ ) spherical nanoparticles with the following characteristics:  $q_1 = 1$ ,  $A_{in} = 0$ ,  $k_\sigma = 0$

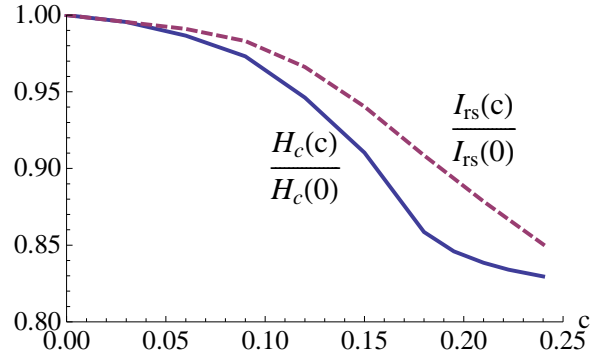


Figure 3: Relative coercive force  $H_c(c)/H_c(0)$  and relative saturation remanence  $I_{rs}(c)/I_{rs}(0)$  on the volume concentration  $c$  of magnetic nanoparticles

## Results and discussion

The influence of magnetic interaction on the hysteresis loop and magnetization curve of the ensemble of nanoparticles  $CoFe_2O_4$   $\gamma$ - $Fe_2O_3$  is shown in Fig. 2. When the volume concentration of magnetic particles becomes significant<sup>2</sup> (e.g.,  $c = 24\%$ , see Fig. 2), the magnetostatic interaction smooths the hysteresis loop and lowers the magnetization curve. The interaction between the particles decreases both the coercive force  $H_c$  (from 1115 Oe to 920 Oe) and saturation remanence  $I_{rs}$  (from 232 G to 198 G). Moreover, the hysteresis characteristics vary non-linearly as a function of the magnetic interaction, and for small values of the volume concentration of magnetic particles (say, equal to  $c = 9\%$ ) are reduced by less than 3% (see Fig. 3).

The reduction of hysteresis characteristics with growth of concentration of magnetic particles is related to disarranging influence of the magnetic interaction on the distribution of magnetic moments.

Fig. 4 shows the dependence of the coercive force  $H_c$  and saturation remanence  $I_{rs}$  on the mechanical stresses  $\sigma$ , which are determined by the dimensionless constant  $k_\sigma = \lambda\sigma/K_A$  (where  $\lambda$  magnetostriction constant,  $K_A$  constant of crystallographic anisotropy). As expected, the stretching decreases the coercive force and the compression increases it, both in an ensemble of non-interacting nanoparticles and interacting nanoparticles (see Fig. 4a). This can be explained by the fall of the critical fields of magnetization reversal under tension and their growth under compression [4]. The saturation remanence of interacting nanoparticles changes in a similar

<sup>2</sup>Here and below, a record  $c = 0$  means that the concentration is small, but nonzero (otherwise the magnetization of the sample would also turn to zero).

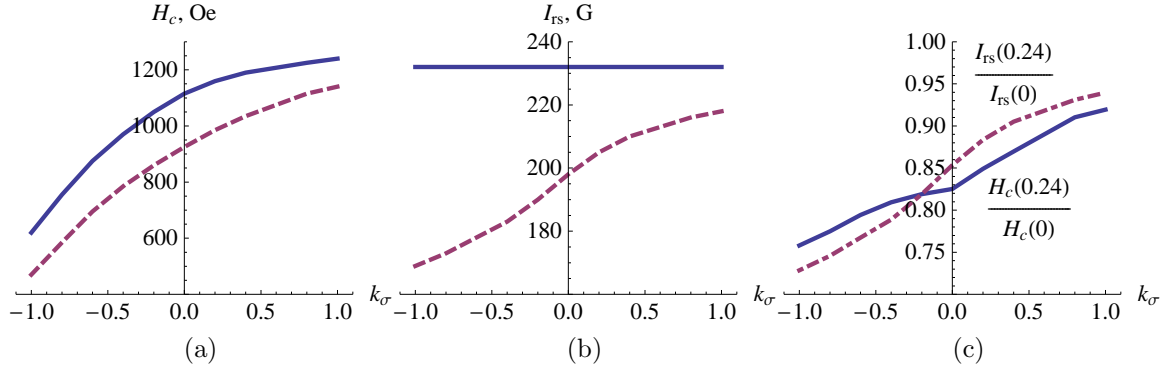


Figure 4: (a) the dependence of the coercive force  $H_c$  and (b) saturation remanence  $I_{rs}$  of an ensemble of non-interacting (*solid curves*) and interacting (*dashed curves*) spherical nanoparticles on the relative stress  $k_\sigma$ ; (c) the dependence of the relative coercive force  $H_c(c = 0.24)/H_c(c = 0)$  and the relative saturation remanence  $I_{rs}(c = 0.24)/I_{rs}(c = 0)$  on the mechanical stresses;  $q_1 = 1$ ,  $A_{in} = 0$

way, due to the mechanical stresses. At the same time, the saturation remanence  $I_{rs}$  of non-interacting nanoparticles is independent on the stresses (see Fig. 4b). Also note that the hysteresis characteristics of an ensemble of interacting nanoparticles under tension vary stronger than in compression. This behavior of  $H_c$  and  $I_{rs}$  is connected to the fact that the magnetostatic interaction stronger shuffles the magnetic moments of low-coercive nanoparticles, and has a smaller influence on the particles in the high-coercive states (see Fig. 4c).

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